INVESTIGATION OF AN IN-SEWER FLOWMETER SUITABLE FOR OPEN-CHANNEL AND PRESSURE-FLOW MEASUREMENT

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POLLUTION CONTROL BRANCH

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ABSTRACT

A U-shaped flume suitable for in-sewer measurement of both open-channel and pressure flows was investigated. Results are presented for experimentation performed over a wide range of discharge at pipe slopes of 0.1%, 0.75% and 1.0%. Methodology is also presented for flume design and the prediction of open-channel rating characteristics for flumes installed at a slope.

Experimental results indicate that measurement of sewer flows under open-channel, two-phase and pressure-flow conditions is feasible with a conventional critical depth flume. Insertion of the flume at different pipe slopes results in measureable changes in open-channel rating characteristics.

A flume design applicable to a specific in-sewer monitoring location requires only the selection of a suitable flume/pipe diameter ratio for the flume geometry tested. Once this ratio is specified, the open-channel rating characteristics for the U-flume installed at a slope can be predicted by a modification of methodology given by the British Standards Institute.

1.0 INTRODUCTION

1.1 Background

Measurement of volumetric flow in a sanitary or storm sewer may be required at a manhole structure or at the point of discharge to a receiving body or treatment facility.

Normally, measurement is least difficult at the point of discharge. Additional constraints apply to flow measurement within the sewer system. Examination of the constraints can assist in the selection of suitable techniques and devices.

Gravity flow sewers are designed to operate under open-channel flow conditions with a free surface. As maximum flows may cause surcharging or pressure-flow conditions, the ability to measure flowrate under both open-channel and pressure-flow conditions is desirable. In addition, an in-sewer flow measurement device should:

- provide minimum interference with sewer hydraulics (avoid significant reduction of sewer capacity or hydrograph distortion),
- be capable of passing suspended and floating solids,
- be unaffected by the in-sewer environment.

Portable or temporary devices should also be capable of installation within the limited space afforded by a manhole and sewer pipe.

The required accuracy of flowrate measurement is dependent on the end-use of the data. For verification and calibration of stormwater management models, both Wenzel (1) and Marsalek (2) have indicated a desired accuracy of 5%. For specifying pipe size, accuracy in the order of 10-15% would be required (3). An accuracy

of 5% is felt appropriate for in-sewer flowmeters used for billing purposes. This accuracy is similar to that of a typical Water Pollution Control Plant flow meter.

1.2 SCOPE

The purpose of this investigation was to evaluate a low cost and practicable method of in-sewer measurement which would meet as many of the above requirements as possible.

While both tracer techniques (2) and ultrasonics (4) have been used to measure pressure and open-channel flow in sewers, a survey of current methodology indicated that a flume would more easily meet these requirements at a potentially lower cost. The University of Illinois (5) and the U.S. Geological Survey (6), have demonstrated that a specialized open-channel flume may be employed for pressure-flow measurement. Such a flume functions under open-channel conditions as a critical depth flume requiring a single point upstream depth measurement. Under pressure-flow conditions the flume behaves as a modified venturi tube, requiring a differential pressure measurement.

The University of Illinois examined a symmetrical pair of semi-circular constrictions with varying constriction ratios. Varying degrees of accuracy were obtained by altering the constriction ratio. The U.S. Geological Survey field tested a U-shaped flume but have not reported details of the performance. For this study a U-shaped constriction was selected which would act as a critical depth flume under open-channel conditions and as a modified venturi tube under pressure-flow conditions.

Design was based on criteria presented by the British Standards Institution (7) for a conventional U-shaped open-channel flume. British Standards, however, specify a horizontal flume installation, impractical for in-sewer application. Owing to the desire to employ the flume in-sewer, the experimental program utilized a conventional flume installed at a variety of pipe slopes.

The specific study objectives were:

1. to obtain rating curves for open-channel, pressure-flow, and intermediate conditions,
2. to examine the effect of slope upon the open-channel rating curves, and
3. to provide user guidance in the selection of a flume design suited to a specific monitoring location and the prediction of the rating characteristics for that flume design.

2.0 FLOW MEASUREMENT

2.1 Open-Channel

Open-channel discharge may be measured by means of a streamlined constriction termed a flume.

For any rate of flow, a flume with sufficient contraction of the flow area will cause critical depth to occur within the flume throat. At critical depth there is a unique relationship between depth and flowrate, and the volumetric discharge can be calculated from depth measurement at a single point.

In practice, the location of the point of critical depth is difficult to predict and varies with flowrate. Accordingly, the depth of flow upstream of the flume is usually measured to obtain the discharge.

The discharge is given by:

$$Q = C_{D_o} \left[\frac{2g\,(d_1 - d_c + LS_o)}{\dfrac{1}{A_c^2} - \dfrac{1}{A_1^2}} \right] \quad - (1)$$

where: Q is the volumetric flow

S_o is the channel slope

L is the distance between point of depth measurement and point of critical depth

A_1 and d_1 are the cross-sectional area and depth of flow at the point of measurement

A_c and d_c are the critical cross-sectional area and critical depth, and C_{D_o} is the open channel coefficient of discharge or the ratio of measured discharge to theoretical discharge.

2.2 Pressure-Flow

Under pressure-flow conditions the proposed flume would operate as a modified venturi tube. The volumetric discharge can be determined by measuring the pressure differential between an upstream location (high relative pressure) and a location within the constriction (low relative pressure). The discharge under pressure conditions is given by:

$$Q = C_{D_P} \left[\frac{(2g\Delta h)}{\frac{1}{A_2^2} - \frac{1}{A_1^2}} \right] \quad - (2)$$

where: Q is the volumetric flow,

Δh is the pressure differential,

A_1 is the upstream cross-sectional area,

A_2 is the constricted cross-sectional area, and

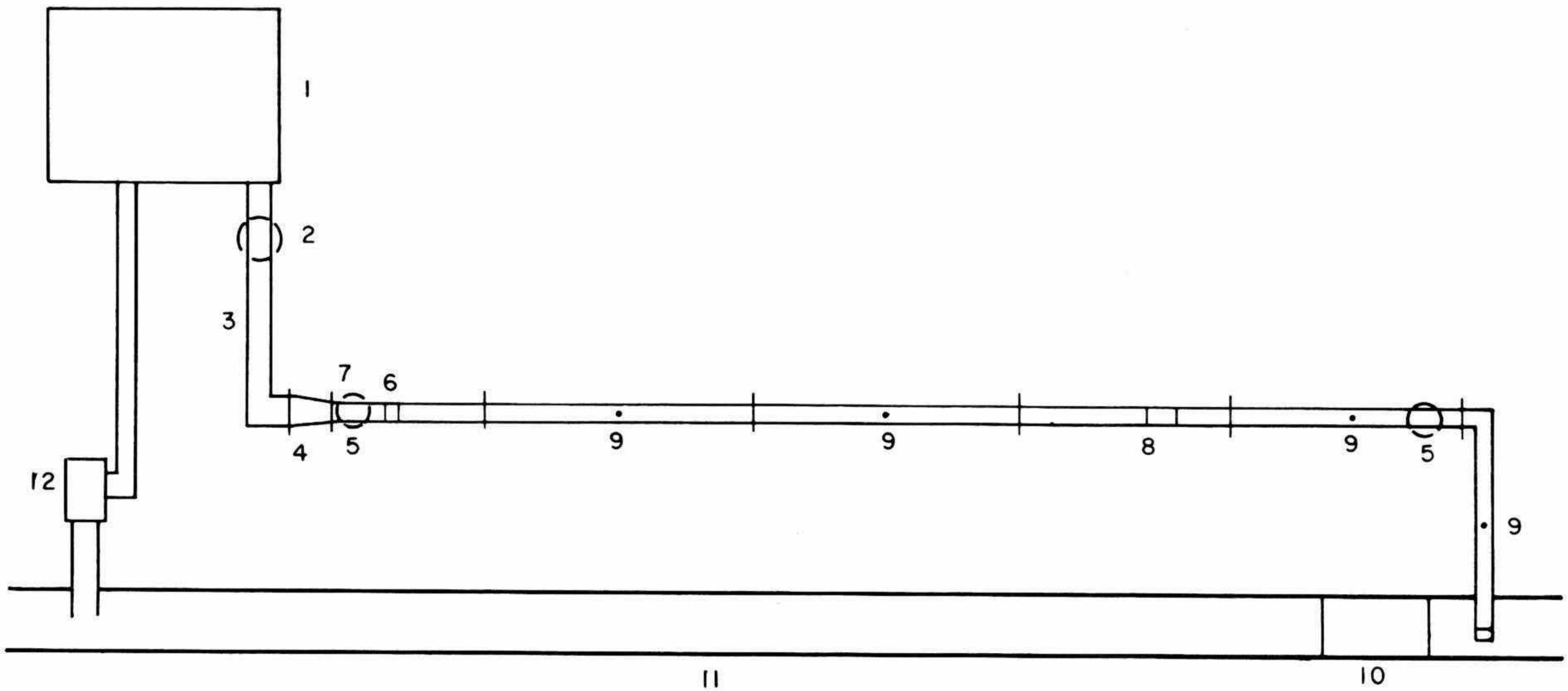
C_{D_P} is the coefficient of discharge for pressure flow or the ratio of measured discharge to theoretical discharge.

3.0 EXPERIMENTAL SYSTEM

Figure 1 is a schematic diagram of the experimental system located at the Hydraulics Laboratory at the Canada Centre for Inland Waters. The system consisted of 23 metres of 250 mm I.D. pipe. The piping material for all but the four metre test section was of Series 125 PVC. The test section was manufactured from cast transparent acrylic pipe to assist in visualizing the flow pattern.

Supports were provided to prevent vertical pipe deflection. The slope was determined by twenty-three measurements of the piping system using an optical level. The relative elevation of any of the reference points could be set to within $\pm$ 1 mm of the calculated value. Lateral alignment was maintained to within $\pm$ 5 mm at the reference sections.

Ventilation to prevent siphoning was provided by 13 mm valved openings in the crown of the pipe at the approximate centre of each pipe section as indicated in Figure 1. These were expanded into 25 mm risers 1.5 m in length. All vents were open during calibration.



1	MAIN VOLUMETRIC AND CONSTANT HEAD TANK	7	LEVEL REFERENCE
2	HEADER CONTROL VALVE	8	FLUME AND TEST SECTION
3	HEADER	9	VENTS
4	REDUCER	10	SMALL VOLUMETRIC TANK
5	SYSTEM CONTROL VALVES	11	RETURN SUMP
6	FLEXIBLE COUPLING	12	PUMP

FIGURE 1: SCHEMATIC OF EXPERIMENTAL FLOW SYSTEM

Flow was provided from a constant head tank to a 41 cm diameter vertical header coupled to the test system by means of a long cone reducer. The system was able to deliver approximately 5 m of static head.

The flowrate was controlled by the combination of a 41 cm butterfly valve in the header system and a 25 cm butterfuly valve in the pipeline.

Low flowrates ($< 0.014\ m^3/sec$) were measured with a small volumetric tank ($2.8\ m^3$) suspended in the sump. For flowrates in excess of $0.014\ m^3/sec$ the laboratory volumetric tank was employed. This tank had an operating volume of $22\ m^3$.

Tappings 4 mm in diameter were made through the pipe invert at intervals throughout the test section to facilitate measurement of either peizometric or differential head. Open-channel water surface profiles were measured with a bank of 6 mm piezometer tubes. Head was determined visually to within $\pm$ 1 mm. For pressure flows a bank of 7 mm I.D. U-tube manometers using 1, 1, 2, 2, tetrabromoethane were employed to measure differential head. Differential head could be read to $\pm$ 1 mm.

The flume geometry illustrated in Figure 2 was taken from specifications given for U-shape flumes by the British Standards Institution (7). The semicircular invert provides a high depth to wetted perimeter ratio at low flowrates. This permits a wide range of measurement under open-channel conditions and easy passage for solids. The area constriction ratio of 0.709 was based on flume geometry suggested by that of the U.S. Geological Survey Sewer Flowmeter (6) and represents a compromise between accuracy and reduction of the carrying capacity of the pipe.

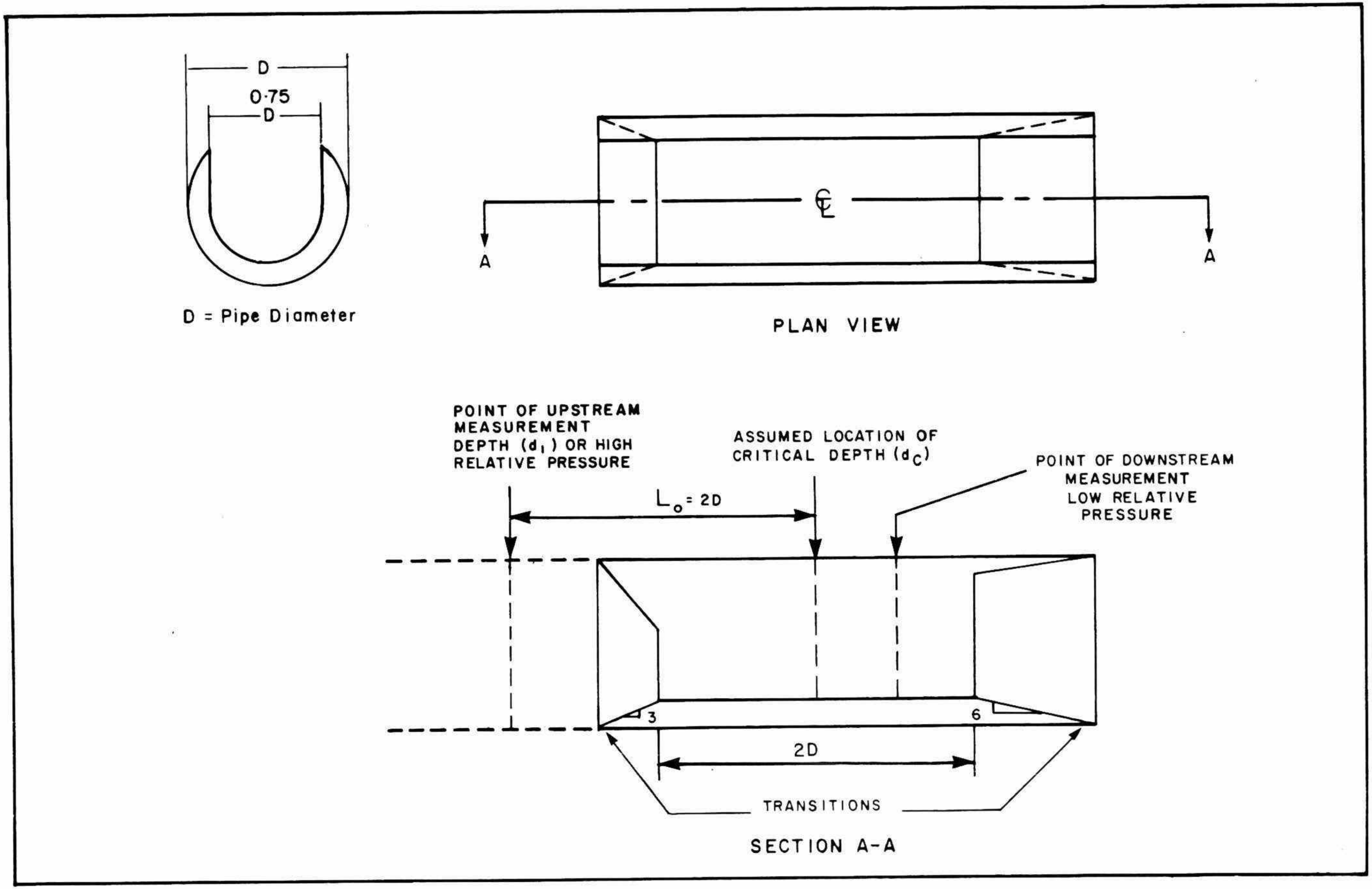


FIGURE 2 : U-FLUME GEOMETRY

The relatively gradual exit transition slope is intended to provide enhanced energy recovery for pressure flows and to allow for large tailwater depths (0.9 d_1) without flooding of the flume throat in open-channel flows.

The location for upstream depth measurement under open-channel flow, and high relative pressure measurement under pressure-flow was 0.5 diameters upstream of the flume. This location is indicated as the point of upstream measurement in Figure 2. For pressure--flow conditions, the point of low relative pressure measurement was located in the flume throat 0.5 diameters upstream of the exit transition. The rationale used in locating these points for measurement was presented by Zukovs (8).

Under open-channel flow conditions the location of the point of critical depth and hence the length L_o varies with discharge. Consistent with findings in the U.S. Geological Survey study (6) and the University of Illinois study (5) critical depth was assumed to occur at the midpoint of the flume throat as indicated in Figure 2. This resulted in an overall length L_o of 2 pipe diameters.

Testing was carried out at channel slopes of 0.1, 0.75 and 1.0%. Depth of flow was varied from 50 mm to full pipe flow. The minimum depth of flow was selected in keeping with the lower depth limit specified by the British Standards Institution. Thirty minutes were allowed for flow stabilization prior to measurement in either open-channel or pressure flow. Forty-five to sixty minutes were allowed in the two-phase flow regime which occurred between the open-channel and pressure-flow regimes.

4.0 QUALITATIVE DESCRIPTION OF FLOW CHARACTERISTICS

4.1 Open-Channel

The limitation of the relatively short pipe reach available for visual flow examination confined observation of flow characteristics to a section of about fifteen diameters centering on the flume. However, the characteristics most likely to affect flume operation occur within this reach.

At the higher discharges, an upstream disturbance was observed at the beginning of the viewing section (approximately 8 diameters upstream of the flume). The disturbance was characterized by surface waves and subsurface aeration.

4.2 Two-Phase Flow

Increases in discharge above the maximum open-channel flowrate initiated two-phase flow conditions. The term two-phase flow is employed here as indicating the simultaneous flow of two media (air and water). The onset of two-phase flow was characterized by the occurrence of slug flow at the pipe crown directly upstream of the flume. Open-channel conditions persisted both up and downstream of the flume and within the flume throat.

At the 1.0% slope, a hydraulic jump was observed upstream of the flume.

Head measurement was not possible when the jump position was within 0.5 diameters of the flume, making flume rating impossible. Testing at constant discharge indicated that with fewer open vents the upstream hydraulic jumps meandered closer to the flume. Accordingly, the degree of venting available may, in practice dictate when measurement is feasible under two-phase flow conditions.

Downstream flow conditions remained open-channel at both pipe slopes until well after two-phase flow existed throughout the upstream reach.

5.0 QUANTITATIVE RESULTS

Figure 3 provides a comparison of the measured and computed flows for the entire range of discharge. As expected the data in general fall below the line indicated for C_{D_o} and C_{D_p} equal to unity. The experimental observations for two-phase and pressure-flow are coincident. A non-ratable region, however, exists between the maximum open-channel discharge investigated and the first ratable discharge (0.044 m^3/s) under two-phase flow conditions.

Increases in channel slope retard the transition from open-channel to the non-ratable region and from two-phase flow to pressure-flow. Channel slope has little effect upon the discharge at which ratable two-phase flow is observed.

The calculated discharge coefficients for open-channel flow and pressure-flow, including the two-phase region, are presented in Figures 4 and 5 respectively. For open-channel flow, results are presented only above a dimensionless depth of 0.20 which is the lower limit of flume application recommended by the British Standards Institute (7). Maximum dimensionless depth for open-channel measurement is 0.9. The sudden increase in C_{D_o} for the 0.1% slope above a dimensionless depth of 0.4 implies the converging flow is causing reductions in throat flow depth to below the critical value. This effect has previously been noted by Ackers (9) in studies of open-channel flumes of various geometry.

With the exception of these results, the average of

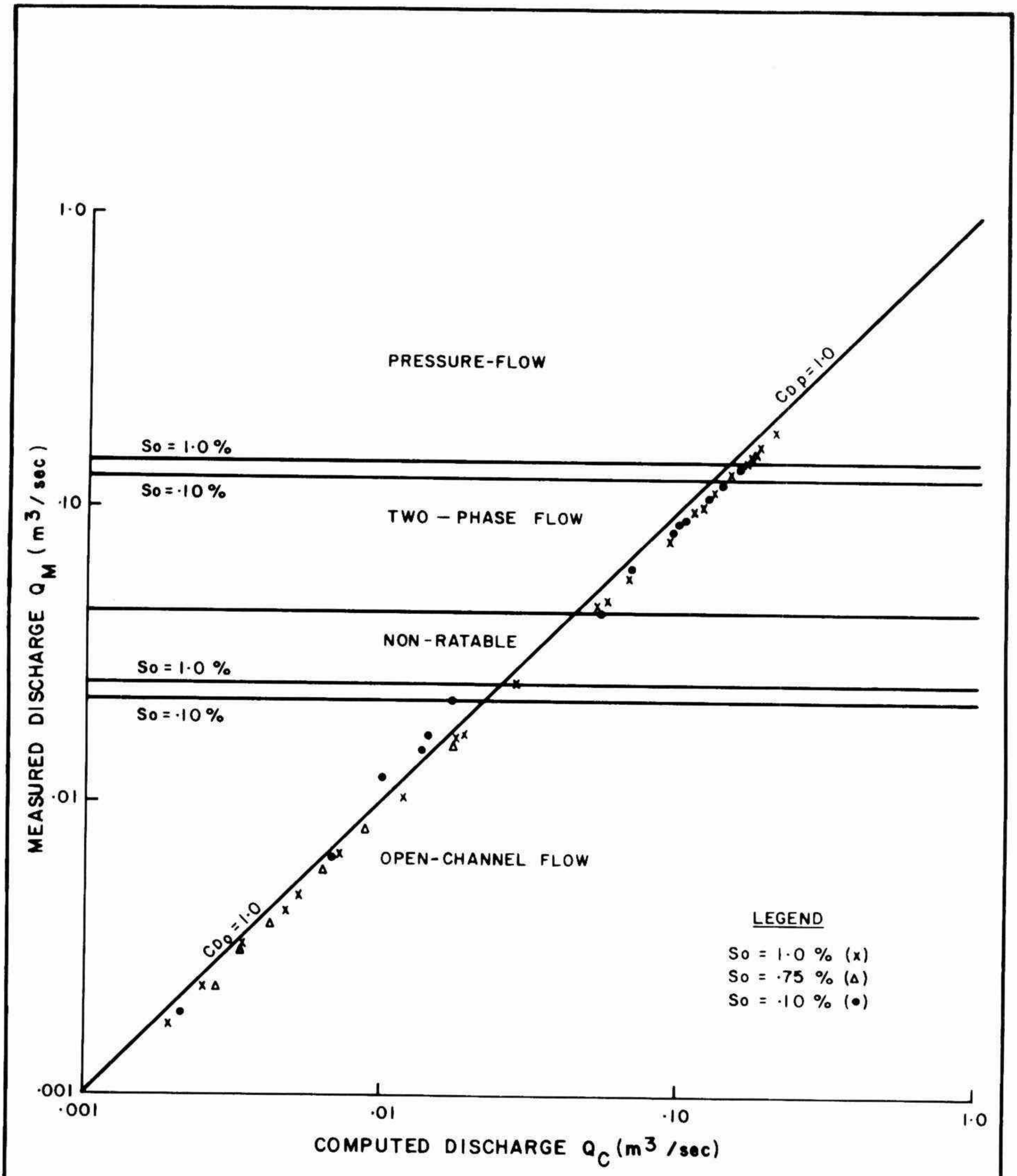


FIGURE 3 : COMPARISON OF MEASURED AND COMPUTED DISCHARGE

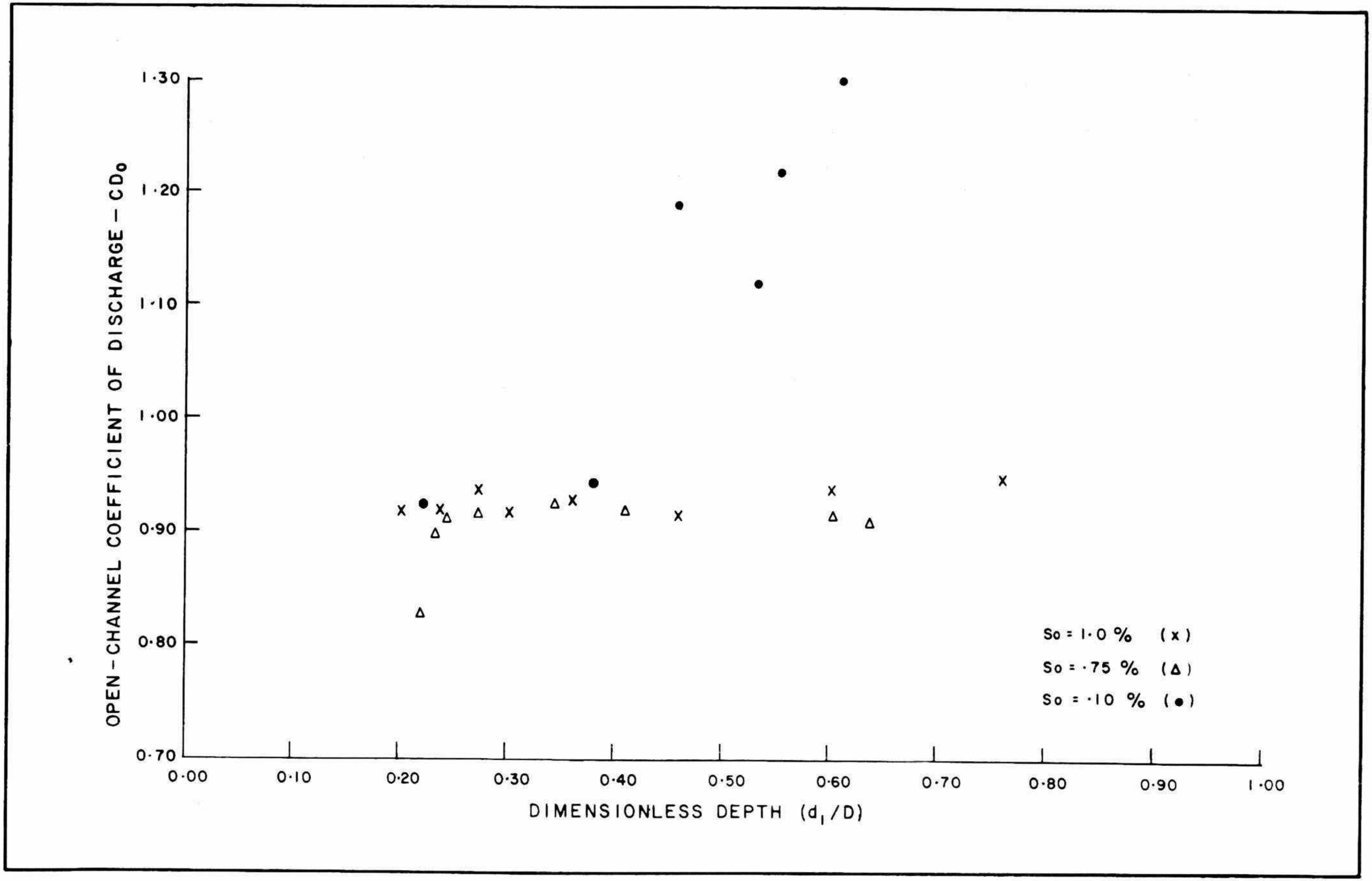


FIGURE 4 : OPEN-CHANNEL COEFFICIENT OF DISCHARGE

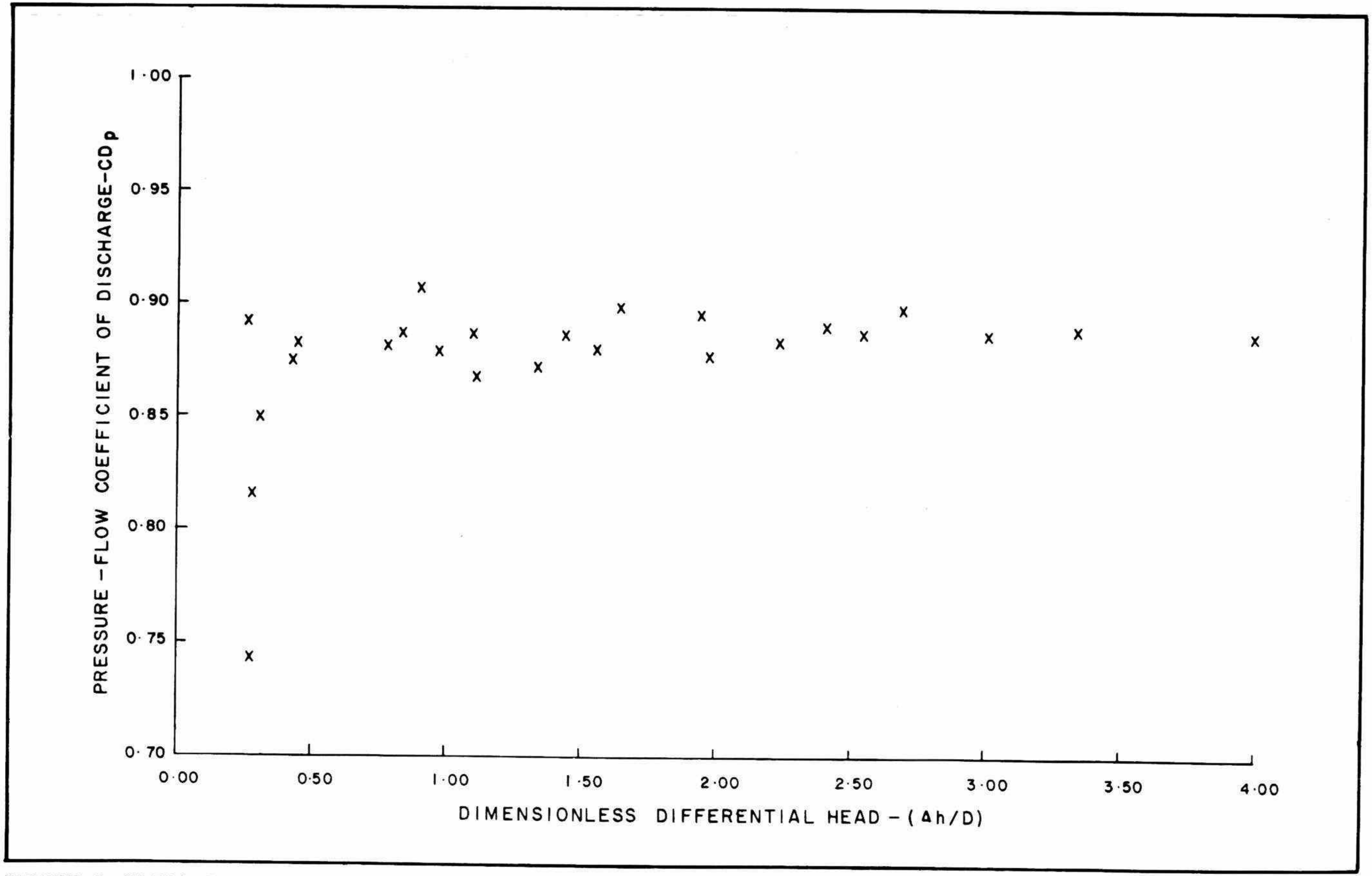


FIGURE 5: PRESSURE - FLOW COEFFICIENT OF DISCHARGE

C_{D_o} values of 0.92 is consistent at three slopes investigated.

Figure 5 indicates that above a dimensionless differential head of 0.50, C_{D_p} has an average value of 0.88, typical of flow tubes.

Flume rating characteristics for discharges ranging from open-channel to pressure-flow are presented in Figure 6. The effect of slope variations (open-channel condition) is not readily evident. However close examination of the data indicates that increases in slope tend to reduce the measured depth for a given discharge. An increase in slope from .1% to 1% resulted in a maximum increase in measured flow of 15%.

As expected, slope exerts no effect upon the two-phase and pressure-flow rating characteristics.

The interference of the upstream hydraulic jump with depth measurement in two-phase flow can be seen by comparing points marked 1 and 2 in Figure 6. Both points were obtained at the same discharge, however, point 1 was measured when the upstream hydraulic jump was in close proximity to the flume.

Placement of the measuring flume in the pipe creates an additional headloss and a corresponding increase in depth of flow. Calculations indicate that flume insertion would result in reductions in the maximum open-channel capacity of a sewer of 41% and 61% respectively at slopes of .1% and 1%. Overall flume head loss under pressure-flow conditions will dictate the increase in sewer surcharge. A plot of dimensionless headloss versus increase in velocity head in the flume throat is presented in Figure 7 for the test flume. At the maximum discharge investigated (0.183 m^3/sec) the headloss was 0.184 m in the test system.

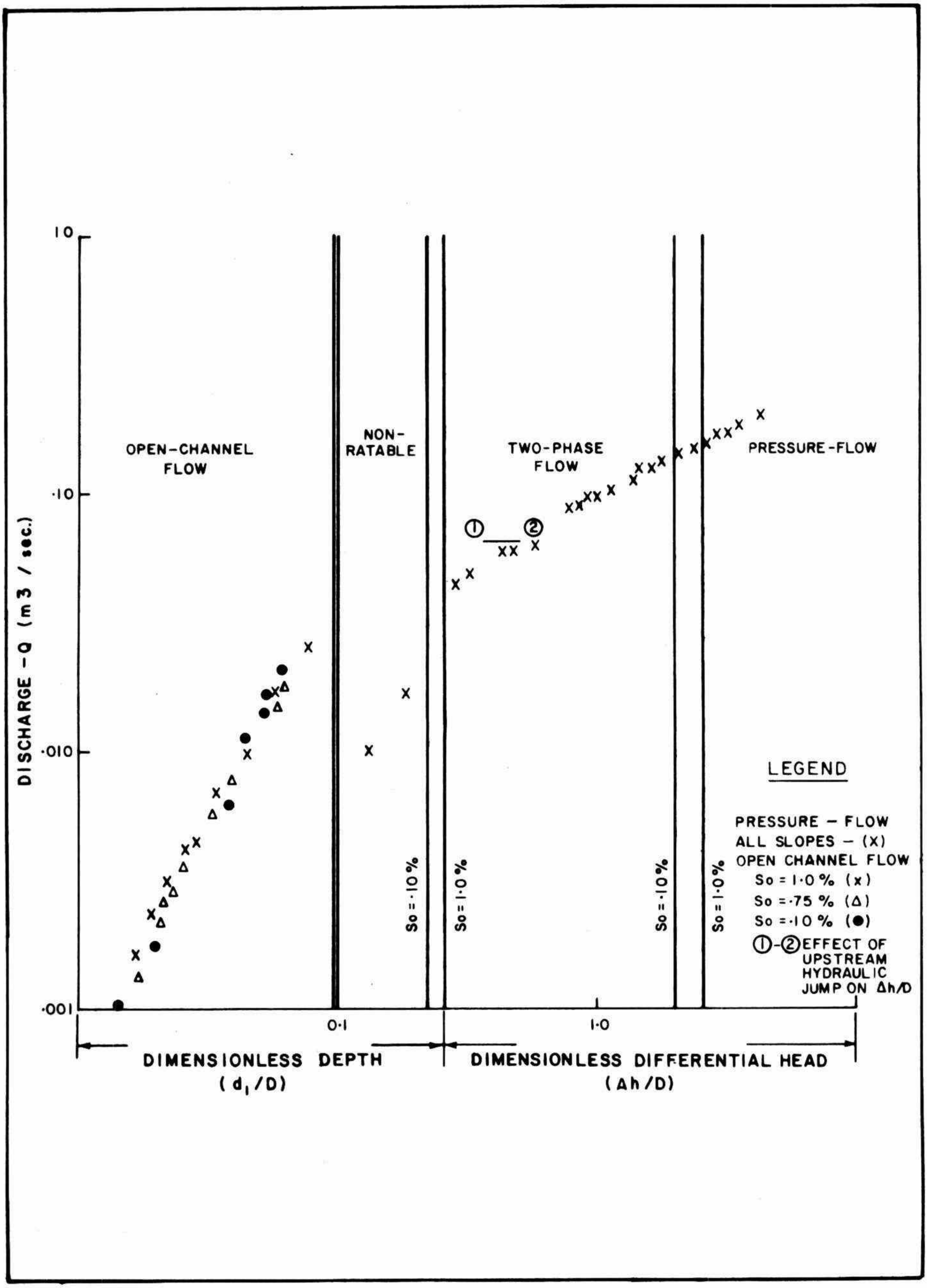


FIGURE 6 : U–FLUME RATING CHARACTERISTICS

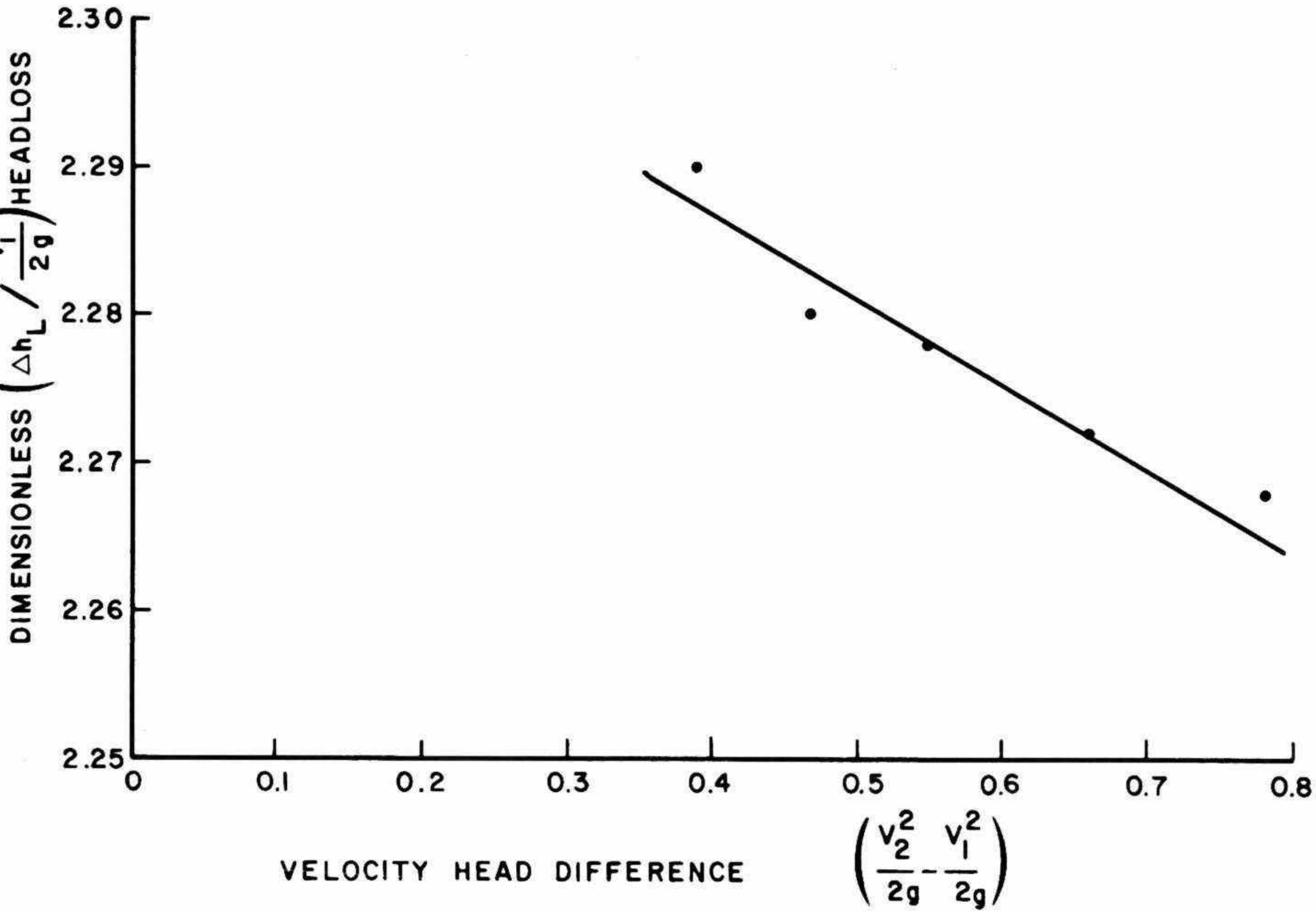


FIGURE 7 : DIMENSIONLESS HEADLOSS UNDER PRESSURE – FLOW OPERATION.

6.0 APPLICATION

The application of the U-flume to in-sewer flow measurement requires the selection of a flume design suited to a specific monitoring location and the prediction of the rating characteristics for that flume design.

British Standards Institute (7) provide a methodology to establish design parameters and rating curves for open-channel flumes. However, the procedure is limited to the open-channel regime and specifies a horizontal flume position. This is not practical for most installations in existing sewers.

6.1 Open-Channel

The design of the U-flume requires the selection of a suitable flume/pipe diameter ratio. Appropriate flume dimensions are specified by Figure 2. The maximum flume/pipe diameter ratio that will give critical depth in the flume throat throughout the entire range of open-channel discharge is given in Figure 8. The ratio varies both with pipe roughness and slope. The values presented encompass conditions ranging from brick sewers ($n = .021$) to plastic sewer pipe ($n = .009$). Ratios smaller than those indicated can be used for a particular slope/roughness combination but will cause increased headloss. The results of Figure 8 are based upon an analysis similar to that given by Wenzel (5).

The British Standards Institute computational procedure must be modified for flume installations at a slope by the addition of the LS_o term to the energy equation (see equation 1). Figure 9 presents a comparison of the open-channel coefficient of discharge (C_{D_o}) calculated from the modified British Standards procedure with selected experimental values

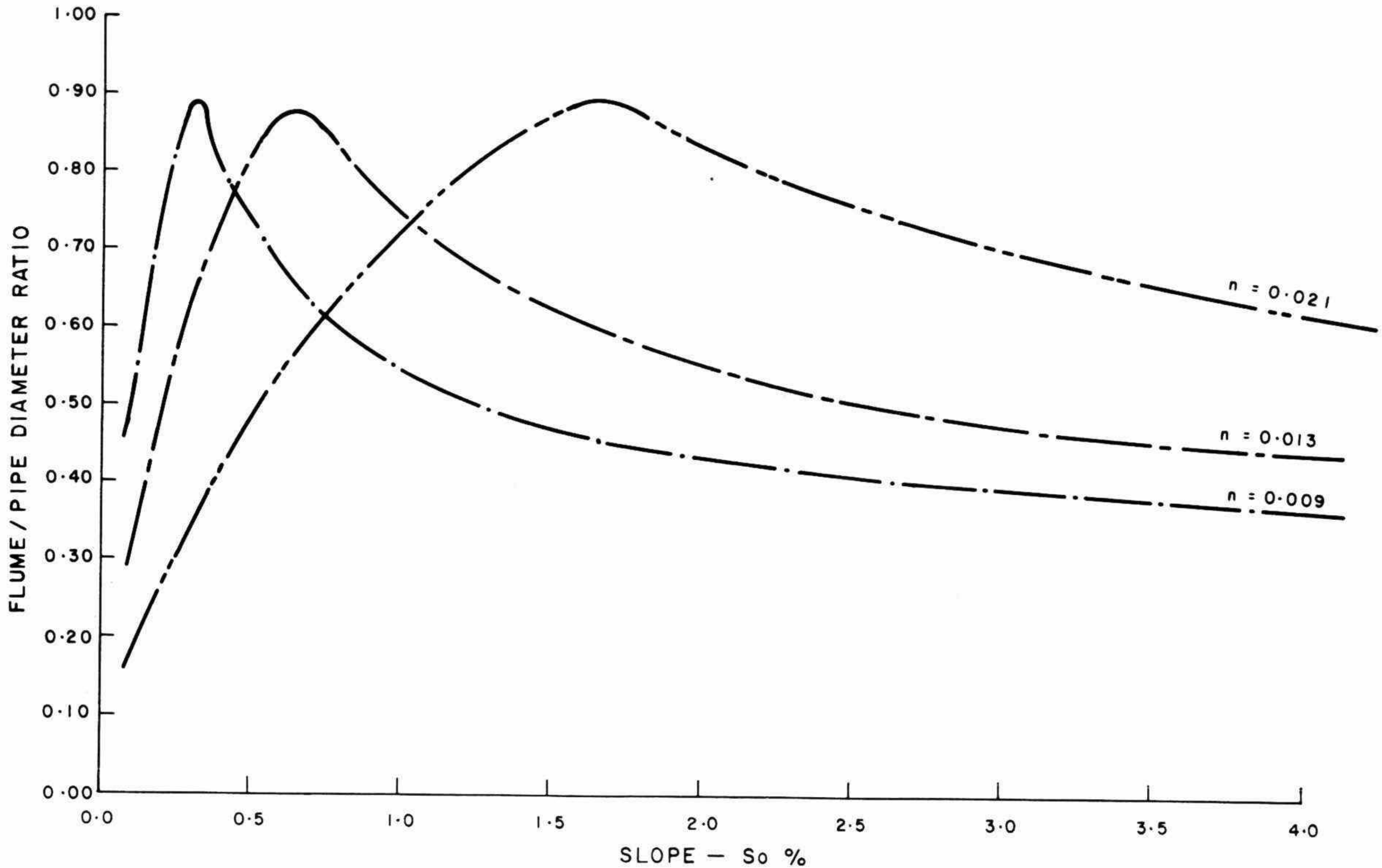


FIGURE 8 : U—FLUME DESIGN DIAMETER RATIO

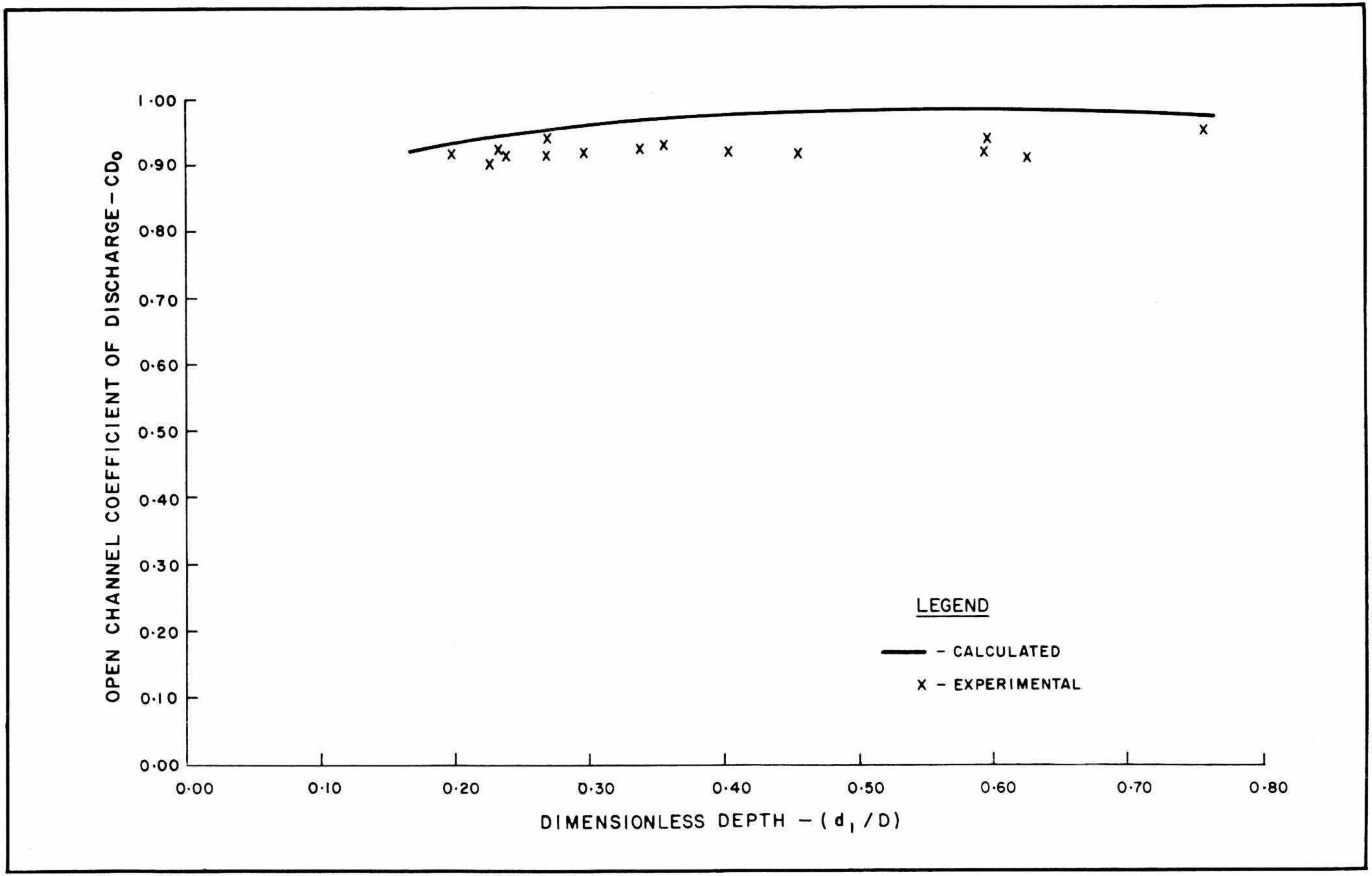


FIGURE 9: COMPARISON OF EXPERIMENTAL AND CALCULATED OPEN-CHANNEL COEFFICIENT OF DISCHARGE

of C_{D_o}. Agreement of experimental and calculated results is generally within 5%, the estimated experimental error.

6.2 Pressure-Flow

Flume operation under pressure-flow conditions is similar to that of a flow tube. This discharge can be determined by differential measurements providing the pressure-flow coefficient of discharge C_{D_p} is known. Figure 5 has indicated C_{D_p} is independent of dimensionless head for values greater than 0.5. Further testing at different flume sizes, constriction ratios and roughnessess is, however, required before C_{D_p} can be specified for conditions other than those investigated.

7.0 CONCLUSIONS AND RECOMMENDATIONS

1) Use of a conventional critical depth flume is feasible for measurement of sewer flows under open-channel, pressure-flow and two-phase flow conditions.

2) Slope exerts a measurable effect on the open-channel rating.

3) Open-channel rating characteristics for a U-shaped flume, installed at a slope can be predicted by a modification of methodology given by the British Standards Institute.

4) A flume design suitable for a specific in-sewer monitoring location can be achieved by selection of a suitable flume/pipe diameter ratio for the flume geometry tested.

In addition, the following recommendations can be made:

1) That additional testing be performed to examine the effects of low slopes ($\sim 0.1\%$) on flume performance.

2) That a suitable means of flume instrumentation and installation be developed and tested.

3) That additional testing be conducted to establish the effect of flume size, roughness and constriction ratio upon the pressure-flow coefficient of discharge C_{D_p}.

4) That additional testing be conducted to establish the effect of pipeline ventilation upon flume performance in the transition from open-channel to pressure-flow.

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